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Kinetic Modeling of Coherent Emission in Coronal Loops: An Innovative Three-Step Numerical Approach

Mehdi Yousefzadeh[1], Alexey Kuznetsov[2], Yao Chen[1], Mahboub Hosseinpour[3]

[1] Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, Shandong 266237, People's Republic of China

[2] Institute of Solar-Terrestrial Physics, Irkutsk 664033, Russia

[3] Department of Physics, University of Tabriz, Tabriz, Iran

e-mail (speaker): yousefzadeh@sdu.edu.cn

Magnetic reconnection is a fundamental process driving energy release during solar flares, occurring at various locations along coronal loops. It accelerates electrons to high energies, enabling them to excite wave modes and produce electromagnetic emissions as they propagate through the solar atmosphere. Decoding flare-associated radio bursts requires understanding how these electrons interact with ambient plasma and how their injection location affects emission patterns.

Our studies employ an innovative three-step numerical approach to investigate how energetic electron injection—at either the looptop (LT) or footpoint (FP)—modifies wave mode excitation along coronal loops. LT injections generate strong, widespread X2 and Z-modes with minimal Langmuir waves, while FP injections produce localized Langmuir wave excitation as electrons ascend, with X2/Z-modes confined near the injection site. These results reveal how emission processes depend critically on magnetic topology and injection geometry.

The LT scenario yields more intense emissions through direct electron cyclotron maser emission (ECME), favoring X-mode polarization. In contrast, FP injections produce weaker plasma emissions via Langmuir wave conversion, typically showing O-mode or weak polarization. These differences help interpret solar radio observations by linking spectral, polarization, and spatial properties to specific acceleration scenarios.

Connecting simulations to observations remains challenging. While spike bursts likely result from ECME, instruments like EOVSA and SRH currently lack resolution to confirm emission sources within coronal loops. Bridging this gap between theory and observation is crucial for advancing solar radio physics, especially in the critical ω_{pe}/Ω_{ce} frequency range (from hundreds of MHz to a few GHz).

My research addresses this by integrating magnetic field extrapolation, guiding-center modeling, and PIC simulations. This three-step methodology effectively analyzes wave-particle interactions in phenomena like spike bursts, where electron velocity distributions reveal key emission dynamics. The approach combines large-scale magnetic modeling with kinetic small-scale physics to examine how injection geometries influence coherent emissions.

By unifying these techniques, our work provides a relatively comprehensive framework for interpreting how electron dynamics shape solar radio emissions. These insights not only clarify existing observations but also establish methodologies for exploiting future high-resolution radio instrumentation. The findings highlight the importance of combining multi-scale simulations with observational constraints to unravel complex flare energetics. The research results are sponsored by the Youth Specialty Category grant under project No. ZR2024QD206.

References

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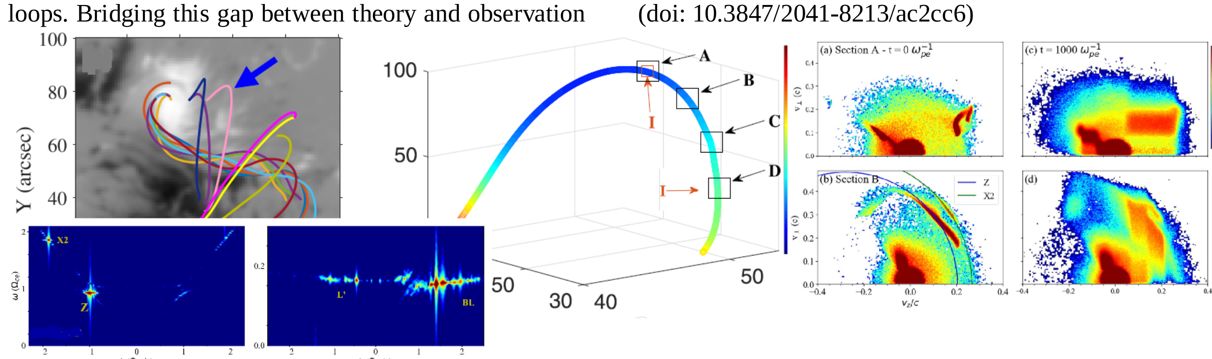

Figure1. (a) shows the background HMI image and some selected magnetic field lines. (b) The letters A–D show the sections within which VDFs will be examined, and the letter I represents the injection location along with the derived VDF and the excited wave modes.